



# Soil Erosion Assessment Using the RUSLE Model, Remote Sensing, and GIS in the Woybo Watershed, Ethiopia

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## Abstract

Ethiopia, a country in the Horn of Africa, is noted for its diverse natural landscapes and rich agricultural legacy. However, it faces a significant challenge in the form of soil erosion and loss. The country's pace of soil loss, particularly in the Woybo watershed, has been a major cause of concern due to its detrimental impact on food security, livelihoods, and long-term development. To construct the soil loss rate map in the Woybo watershed, the Revised Universal Soil Loss Equation (RUSLE) was integrated with Remote Sensing and Geographic Information System. The RUSLE model was used to analyze soil erosion using rainfall erosivity, soil erodibility, slope length and steepness, land cover and management, and conservation support practice. The calculated average soil loss rate from the watershed was 19.58 tons per hectare per year, resulting in a total annual erosion rate of 572,611.15 tons per year. Furthermore, nearly half of the watershed (47.78%) is affected by very slight to moderate and very severe (39.96%) soil losses. Furthermore, the western portion of the watershed is predominantly composed of brown soil, which is intrinsically more sensitive to the eroding force of rainfall droplets. The majority of the watershed's eastern half is made up of red soils, which are significantly influenced by soil loss and erosion. Managers and policymakers can use the findings of this study to establish suitable conservation programs, ensuring that water and soil conservation measures are implemented quickly in the study watershed, in accordance with the priority watersheds' ranking.

**Keywords** Ethiopia · Prioritization · RUSLE · Soil loss · Woybo

## Introduction

Soil erosion is a significant environmental issue in both developed and developing nation states. Globally, soil erosion affects land productivity by losing nutrients and organic matter, resulting in lower crop yields and water quality. A critical concern with agricultural land deterioration is the occurrence of soil erosion, which is now recognized as a major environmental threat worldwide [38, 41]; this significantly influences the economy and the environment [57]. Soil erosion also affects afforestation activities by forming rills, reducing arable land through gully formation, and limiting access to cultivation. Ultimately, soil erosion yields considerable additional input

costs, leading to overall economic loss in the agricultural industry, painful environmental impacts, and drought. However, the negative effect of soil erosion is most common and severe in agrarian peoples of developing countries, which are economically unprivileged, face technology inaccessibility, and have a lower capacity to overcome erosion-induced shocks [24]. It can also lead to increased water storage costs as well as sediment build-up in streams, rivers, and lakes. It is one of the most serious issues because it depletes the topsoil of vital plant nutrients and subsequently increases the expected level of sedimentation in rivers and reservoirs, which decreases the size of those bodies of water to store water and decreases the amount of water available to plants [16].

The actions of geomorphic driver factors like hydrogeological systems, rainfall, soil characteristics, and topographical features, are what is known as the “geomorphic drivers” that control soil erosion globally. Despite the fact that erosion is a natural phenomenon, human action has increased the worldwide rate of erosion by ten to fourteen

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times. Deforestation, anthropogenic climate change, agricultural activity, urban sprawl, soil degradation, and road construction are some of the most momentous human actions in terms of their effect on promoting erosion [17].

There are various stages of soil erosion, including gully, sheet, and rill erosion which involve the detachment, transport, and accumulation of soil particles in the catchment region, which deteriorates the quality of soil and lowers the productivity of potential lands [22]. According to Arabameri et al. [3] and Band et al. [5], soil erosion is the primary source of water pollution and the most pervasive type of degradation of land worldwide. Soil erosion is responsible for up to a 17% decrease in crop yield on about 85% of the world's degraded land [47], resulting in the annual obsolescence of 10 million hectares of land [49]. Among many other external issues, the storage capacity of reservoirs is decreased at a proportion of roughly one percent annually [42].

Among other natural risks of damage caused by a geological process, the intensity of rainfall, marginal landforms, and the susceptibility of soil to detachment during torrential downpours are all natural factors that cause soil erosion [12, 43, 48, 50]. However, it is sped up by artificial factors like poverty, forest clearing, and population growth [19, 39]. By means of improved management and sustainable planning, it is only possible to prevent the diminution of natural resources, preserve biodiversity, and maintain the soil's ongoing productivity [13, 53, 54]. Natural processes such as soil erosion that are connected to the hydrologic cycle are common geological occurrences. When water separates and removes soil particles from the soil, a gradual process of soil degradation takes place. There are two aspects that pertain to soil erosion in catchment regions and the consequent sedimentation in reservoirs, lakes, and rivers. The catchment areas' fertile, rich soil is first eroded. In addition to the deterioration of water quality downstream, there is also a decrease in reservoir capacity. Erosion of the soil leads to soil loss. Consequently, crop yield is decreased as well as soil fertility. Although complete elimination of soil erosion is unattainable, it can be somewhat reduced. In the context of modeling soil erosion and evaluation of erosion risk, the application of Geographic Information System (GIS) technology holds considerable potential for inventorying soil erosion [18].

According to Blanco and Lal [9], approximately one billion people worldwide are affected by soil erosion, roughly half of whom live in Africa. Ethiopia has the tremendous potential to increase the efficiency and production of agriculture, but due to a number of factors that are escalating susceptibility, it is unable to address the root causes of food insecurity, the main ones being land degradation brought on by irregular and insufficient rainfall

deforestation, and erosion of soil. Ethiopia is one of the most environmentally vulnerable countries in the world to accelerated soil erosion. It is estimated that the nation loses one to seven billion tons of carbon annually, costing the nation about one billion ETB [2]. In Ethiopia, the majority of reservoirs constructed for various uses are filled with sediment in less time than half of the projected service life [10]. The Ethiopian highlands are regarded as one of the most severely degraded regions in the world. In Ethiopia, severe land degradation risk is generally attributed to a number of major factors, including soil erosion. This situation threatens both the survival of the vast majority of rural residents and the productivity of their agriculture. As a result, organic matter and nutrients are being depleted from the soil at a much higher rate and faster than they can be replaced. According to the Ethiopian Highland Reclamation Study [20], water erosion takes nearly 1.9 billion tons of productive soil out of the mountains every single year.

RUSLE-based decision-making processes aided by remote sensing GIS technologies are widely used for identifying high erosion potential areas and modeling losses of soil in various regions of the country [26, 33, 35, 36, 46, 58, 65, 67]. The RUSLE model is also the most generally used procedure due to its ability to quantify annual soil loss and harmony with the ArcGIS interface and remote sensing (RS) [37, 57] and the model's applicability to small and large-scale soil erosion studies [21]. The RUSLE model predicts the spatial distribution of soil erosion with fewer data [15, 27, 59, 61, 62]. Topography, soil type, land use pattern, and climate are the input parameters required for RUSLE to predict soil loss [6]. Remote sensing and geographic information systems (GIS) have been extensively employed to pinpoint, delineate, and calculate potential areas of soil erosion across diverse locations [6].

Utilizing the RUSLE model, the present research aimed to estimate the soil erosion rate and develop a soil erosion intensity map for the Woybo watershed. It is crucial to note that all factor maps for the study area were created as a convenient abstraction, ensuring simple access for users in foreseeing potential soil erosion in the current study.

## Materials and Methods

### Background of the Study Area

The research was carried out within the Woybo River catchment, situated in the Southern Ethiopia region and forming a part of the Omo-gibe River Basin. It lies between 37° 30' 37.09" to 37° 52' 14.64" E longitude and 6° 52' 24.9" to 7° 9' 56.99" N latitude. The study encompasses an

approximate area of 600 km<sup>2</sup>. As illustrated in Fig. 1, the map depicts the study area.

In light of a comprehensive data collection from six meteorological stations spanning the years 1990 to 2021, it has been observed that the average monthly temperatures tend to rise during the shorter duration rainy season, which typically occurs between the months of March and May. Conversely, the average monthly temperatures exhibit a downward trend during the longer duration heavy rainy season, which usually takes place from June to September. Meanwhile, the average annual rainfall, based on 32 years of rainfall data, ranged from 1564.20 mm in Areka to 1228.66 mm in Wolaita-Sodo station.

## Data and Methods

During this research, comprehensive data regarding meteorological conditions was gathered from six specifically chosen rain gauge stations, as depicted in Fig. 1, for the duration of 1990 to 2021. The National Meteorological Agency of Ethiopia (NMAE) served as the source of this information. As illustrated in Table 1, this data includes the meteorological station, their respective coordinates, elevation, and the average annual rainfall of the study area.

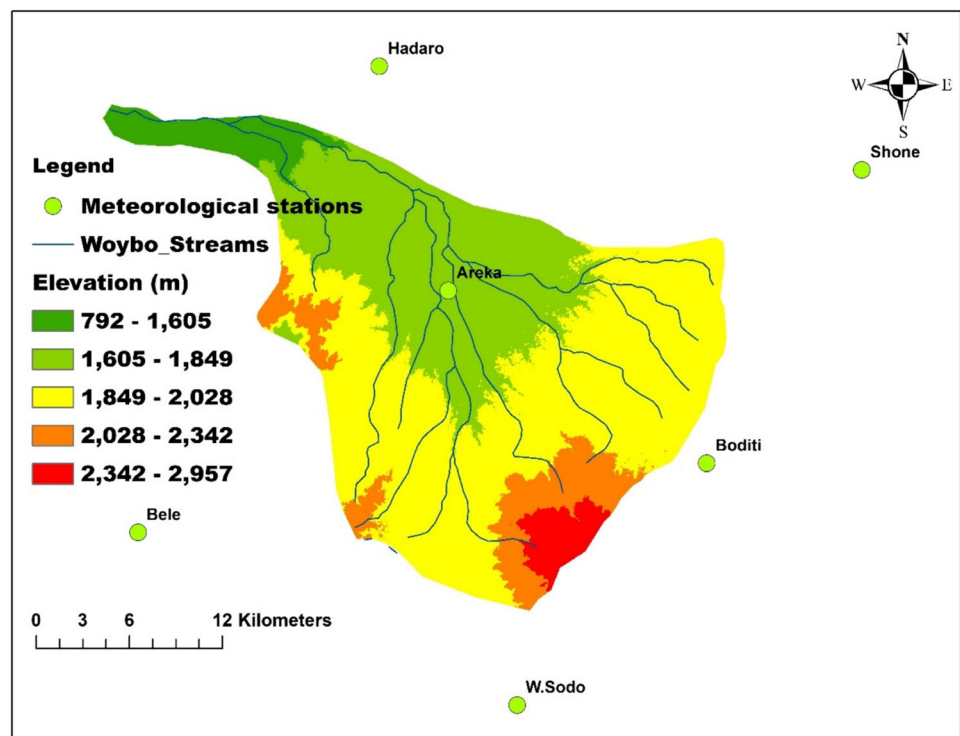
The RUSLE model was applied to analyze the average yearly soil loss that necessitates soil types and properties, taking into account precipitation, slope length and steepness, land use, and land cover maps, as well as cover

management practices. The elements of this approach are straightforwardly identified and have the potential to be easily combined with Geographic Information System (GIS) software for enhanced analysis. This is the most effective model currently accessible for application at the watershed or basin level. The data inputs for the study were acquired from satellite imagery, (including land use/land cover (LU/LC) maps, digital elevation models (DEM), and soil information), and meteorological data (such as precipitation) were then combined into the RUSLE approach. This model is more suited for small watersheds [11, 51]. Finally, based on the RUSLE model parameters, the area was then segregated into hydrologically homogeneous cells with a size of 20 m × 20 m.

## Soil Loss Estimation

In order to calculate the mean annual soil loss within the Woybo watershed, the Revised Universal Soil Loss Equation (RUSLE), enclosed with GIS and remote sensing methodologies, was applied. Renard et al. [52] originally developed the RUSLE as a tool for predicting soil loss from agricultural lands. Thus, for this investigation, the RUSLE approach was adapted for application at the watershed level. This model establishes a relationship between the average annual soil loss (A) per unit area and several contributing factors including slope length/steepness (LS), cover-management (C), rainfall-runoff erosivity

**Fig. 1** Location map of Woybo watershed



**Table 1** Mean annual rainfall and R-Factors of the six meteorological stations around and inside Woybo watershed

Stations	Location (Dec. Deg.)		Elevation (m)	Mean annual rainfall (mm)	R-Factor MJ mm ha/hr/yr
	Long	Lat			
Areka	37.71	7.06	1752	1564.20	869.07
Bele	37.53	6.92	1240	1238.34	765.80
Bodity	37.86	6.96	2043	1292.07	727.49
Hadero	37.67	7.19	1657	1261.80	764.79
Shone	37.95	7.13	1959	1426.66	758.77
W.Sodo	37.75	6.82	1854	1228.66	758.94

(R), soil erodibility (K), and support practice (P), which are associated with both rill and sheet erosion. These factors can be empirically determined and subsequently summarized as:

$$A = R * K * LS * C * P \quad (1)$$

In the context of the equation, the variable A represents the annual soil loss measured in tons per hectare per year ( $t \text{ ha}^{-1} \text{ year}^{-1}$ ). The variable R denotes the rainfall erosivity factor expressed in terms of  $\text{MJ mm h}^{-1} \text{ ha}^{-1} \text{ year}^{-1}$ . The parameter K signifies the soil erodibility factor, which is quantified in units of tons per hour per megajoule per millimeter ( $t \text{ hr. MJ}^{-1} \text{ mm}^{-1}$ ). The LS factor encompasses slope length and slope steepness and is dimensionless. Factor C represents the cover management factor and is also dimensionless, while factor P stands for the conservation practice factor, which is likewise dimensionless. By utilizing the geomorphological characteristics and rainfall patterns specific to the area under study, it is possible to estimate the values for soil erodibility, erosivity, and management practice factors. Supplementary Fig. 1 depicts the workflow and methodology of this research work.

### Rainfall Erosivity Factor (R)

In the field of soil science and hydrology, the rainfall erosivity factor (R) plays a crucial role as a parameter featured in both the Universal Soil Loss Equation (USLE) and its revised version, the Revised Universal Soil Loss Equation (RUSLE). These equations are widely utilized for the estimation of soil erosion resulting from the combined effects of rainfall and runoff. The R-factor measures rainfall's erosive power and measures rainfall's potential to produce soil erosion. It considers the intensity and frequency of rainfall occurrences. The higher R-values indicate more erosive rainfall conditions. Important characteristics of precipitation and also have more considerable annual variations [23]. The R-factor is computed by multiplying the total energy of the storm by the maximum rainfall intensity measured using autographic

recorders in 30 min [52]. Due to the paucity of records of the maximum 30-min rainfall intensity in the study area, the R factor in this study area was calculated utilizing average annual rainfall data (Eq. 2), which is based on the approach designed by Hurni [35] for the Ethiopian highlands. By employing precipitation data spanning a period of 22 years, a spatial layer representing rainfall across the catchment area was generated through the application of the ordinary Kriging interpolation technique within the ArcGIS platform. Given that the constant mean of the data across the basin is not known, the ordinary Kriging method, utilizing the spherical semivariogram model, was selected for the interpolation process. Ordinary Kriging is the most commonly employed kriging technique and is particularly useful for estimating values at specific points within a region where a variogram is available. This method utilizes data from the vicinity of the estimation location to make accurate predictions [63].

$$R = -8.12 + (0.562 \times P) \quad (2)$$

In the equation, the variable R represents the rainfall erosivity factor expressed in terms of  $\text{MJ mm h}^{-1} \text{ ha}^{-1} \text{ year}^{-1}$ , while P denotes the annual rainfall (mm), which is obtained from the spatial layer of rainfall derived through ordinary Kriging interpolation.

### Soil Erodibility Factor (K)

The soil erodibility factor, sometimes known as the “K-factor,” is a parameter used in the USLE and RUSLE metrics. These equations are frequently used to calculate soil erosion rates. The K-factor represents the vulnerability of a specific soil to water erosion. Several soil properties influence the K-factor, including texture, structure, organic matter content, and permeability. Higher K-factors are seen in soils that are more prone to erosion. Organic matter reduces the risk of soil erodibility and detachment while increasing infiltration. The K-factor pertains to the tendency of soil particles to undergo erosion due to the impact of rainfall and runoff. A higher K factor indicates that the

soil is more prone to erosion, as it suggests an increased susceptibility to the erosive effects of rainfall and runoff.

Soil databases and field testing are commonly used to calculate the K factor. It is classically stated in tons per hour, Mega joules, and millimeters of rain (tons/hour/MJ/mm). The K factor is calculated experimentally for a given soil type and reflects the physical and chemical features of the soil that contribute to its erosion potential.

The availability of soil data in an area determines the choice of methods for determining K factor values. Different authors adopt different methods to describe the K factor of soils [52]. It is crucial to note that different locations or countries may use different techniques to calculate the soil erosion factor, depending on local erosion patterns and soil features. Furthermore, in some solicitations, the Revised Universal Soil Loss and Runoff Model (RUSLE2) has replaced the RUSLE model. The susceptibility of soil to erosion, known as soil erodibility, is influenced by its biochemical and physical properties. This characteristic can be quantified on a scale ranging from 0 to 1, reflecting varying degrees of erodibility. The K factor varies from nearly 1.0 in the worst-case scenario to under 0.1 for the least erodible soils. The soil textural nomograph is a widely utilized tool for determining soil erodibility values. Consequently, calculating the Soil erodibility factor values necessitates data on several parameters when all influencing factors are available. These parameters include the percentages of silt, clay, sand, and gravel, the percentage of organic matter, and classes for soil structure and permeability according to the nomograph by [64]. However, due to the unavailability of data needed to obtain these nomograph parameters at the local level, the K-factor for this study was derived from [34, 35]. They provided K-factor values suitable for Ethiopian conditions based on soil color, which is considered indicative of soil properties. Four distinct soil colors were identified—black, brown, red, and yellow—with corresponding K-factor values of 0.15, 0.20, 0.25, and 0.30, respectively (Supplementary Table 1). Based on this, the K-factor consignment and map conversion were carried out in a 20 × 20-m grid cell.

### Topographic Factor (LS)

The topographic factor (LS) considers the impact of slope length (L) and steepness (S) on soil erosion. It is one of the primary parameters used to determine the likelihood of soil erosion in a given location. The slope length factor (L) describes the influence of slope length on soil erosion. Lis is the horizontal distance between the place where runoff originates and the point where runoff enters a well-defined channel that may be part of a drainage system [64]. Longer slopes provide a higher risk for erosion. Slope Steepness Factor (S): This factor takes into account the

influence of slope steepness on soil erosion. Steeper slopes have a higher possibility for erosion.

The increasing slope length and steepness increase the velocity and volume of surface runoff, resulting in more significant soil loss in the given area [51]. As a result, they are considered combined in erosion prediction. However, several scholars used an undeviating gradient plot to assess the influence of slope length and steepness individually [52].

Many researchers have devised and implemented various ways for estimating the LS factor (dimensionless) [66]. Wishmeier and Smith [64] proposed the following equation for determining the LS factor:

$$LS = \left( \frac{x}{22.13} \right)^m (0.065 + 0.045s + 0.0065s^2) \quad (3)$$

In the equation, LS represents the topographic factor, where x denotes the field slope length, which can be computed by multiplying the flow accumulation with the resolution of the Digital Elevation Model (DEM), while s signifies the slope gradient expressed as a percentage. It's important to note that the value of m doesn't carry the same significance universally or under all circumstances within a particular location. The m values exhibit variation, typically falling within the range of 0.2 to 0.5, depending upon the slope conditions. For instance, if the slope exceeds 5 (m = 0.5), lies between 3 and 5 (m = 0.4), ranges between 1 and 3 (m = 0.3), or is less than 1 (m = 0.2), distinct values of m are assigned accordingly [64].

However, for the specific case of Ethiopia, Moore and Wilson [45] provided an equation that has been widely utilized and tested in many Ethiopian studies. It is stated as follows:

$$LS = P (FA \cdot \text{cell size} / 22.13, 0.6) * P (\sin (\text{slope} * 0.01745) / 0.0896, 1.4) \quad (4)$$

where P = power and FA = flow accumulation.

### Cover and Management Factor (C)

The C factor describes how land uses, land cover and crop management practices influence soil loss as compared to losses from bare fallow lands [32]. It represents the effect of vegetation and land management practices on soil erosion. It is the reduction of soil erosion caused by vegetation canopy and ground cover [52]. The C value is dynamic, changing seasonally based on changes in vegetation cover throughout time [7]. The C factor is defined as the ratio of soil loss from specified crop fields to the corresponding loss from tilled, bare test plots ploughed up and downslope [30].

The values of cover and management factor (C) depend on the type of vegetation, growth stage, and coverage



percentage. The vegetation cover has the greatest influence on erosion because it prevents and dissipates the energy of raindrops' impact on the soil surface. It also describes the effects of land use and land cover types on soil loss, and the value was obtained from the LULC map. Using reclassification tools in the ArcGIS 10.7.1 environment, the corresponding C-values were assigned to each land use and land cover class. At the conclusion of this process, a raster layer portraying C-factors was generated for the selected study area. This was achieved through the assignment of a customized C value to individual land use and land cover classes within the given study region.

### Support Practice (P) Factor

The erosion support practice factor, denoted as a ratio, serves as a comparative measure by comparing the estimated soil losses attributed to a specific conservation technique against those determined for conventional up and down-slope tilling practices [64]. Thus, by gathering data from field assessments, the P-factor for RUSLE can be mapped [8]. Despite that, because there were no conservation measures took place in the Woybo watershed study region, and data on persistent management techniques were unavailable, it is better to apply the P-factor proposed by [64]. Different researchers have utilized this approach in Ethiopia's highlands [8, 29, 44]. This approach involves the classification of land into three distinct categories, namely cultivated land, shrub land, and other land. Regardless of the slope, a *P* value of 0.8 was designated for shrubland, while a *P* value of 1 was assigned to other land use classifications. Despite that, the *P*-value for agricultural land was assigned a value based on its slope and has been divided based on the six slope classes: 0–5, 5–10, 10–20, 20–30, and > 50% [4, 14, 28, 60, 64].

### Prioritization for Soil Conservation Planning

Due to the constraints in resources, it is not feasible to implement soil conservation measures throughout the entire watershed simultaneously. Consequently, it is crucial for land managers and policymakers to prioritize intervention areas, also known as erosion hot spots, based on the risks of soil erosion and severity. This prioritization allows for more effective planning and the implementation of suitable intervention measures, as highlighted by [25, 28, 40, 55]. Therefore, considering factors such as the national average soil loss rate, the soil loss tolerance of the area, the relative erosion status of the watersheds, the severity class of soil erosion, and the estimated rates of erosion, the Woybo watershed has been classified and

ranked into five priority classes. These classifications include: very slight ( $0\text{--}5\text{ t ha}^{-1}\text{ yr}^{-1}$ ), slight ( $5\text{--}15\text{ t ha}^{-1}\text{ yr}^{-1}$ ), moderate ( $15\text{--}30\text{ t ha}^{-1}\text{ yr}^{-1}$ ), severe ( $30\text{--}50\text{ t ha}^{-1}\text{ yr}^{-1}$ ), and very severe ( $> 50\text{ t ha}^{-1}\text{ yr}^{-1}$ ) [68]. The utilization of this classification serves the purpose of assessing and establishing the significance of preserving the land to mitigate potential erosion hazards and associated risks. Regions identified as being at the highest risk of severe erosion were assigned the highest priority for soil conservation planning, whereas areas with lower erosion risks were given correspondingly lower priority. Consequently, it is essential that the most erosion-prone areas receive immediate.

### Land Management Strategies

Strategies for land management, focusing on conservation technologies, play a pivotal role in mitigating soil erosion, preserving soil integrity, and enhancing water infiltration. It is imperative that the chosen land management strategies align with the specific characteristics of the terrain, land use patterns, and the preferences of local communities. Various soil and water conservation methods have been adopted worldwide, leading to notable reductions in soil erosion following their successful implementation. For instance, integrating practices such as cut and carry systems for mountain pasture utilization, terracing, and agroforestry proves effective in sustainably managing erosion-prone areas within steep mountain ecosystems. Thus, this study examines globally recognized conservation techniques for long-term soil and water conservation in the Ethiopian Highlands. Notably, slope is a critical factor to consider when proposing conservation interventions. Drawing from data provided by the Revised Universal Soil Loss Equation (RUSLE), several conservation techniques have been employed to mitigate soil erosion risks on sloping or highly sloping cultivated lands by various researchers [1]. These techniques include soil bunding, runoff diversion, hillside terracing tailored to sub-watersheds based on slope percentages, and the construction of check dams. The integration of these diverse land management strategies over time holds the potential to enhance livelihoods, reduce soil erosion hazards, rehabilitate degraded lands, and rejuvenate the ecological balance within the catchment areas of local communities. In essence, it is advisable to prioritize the implementation of appropriate soil and water conservation practices in erosion hot spot areas before extending these efforts to other regions, taking into account the severity of constraints and the availability of resources.

## Results and Discussion

### Rainfall Erosivity Factor (R-Factor)

The R-factor indicates the influence of rainfall on erosion in  $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{year}^{-1}$ . The R-factor values obtained from six rain gauge stations to be found both around and within the Woybo watershed were utilized for the development of a comprehensive rainfall-runoff erosivity map which is covering the Woybo watershed. This mapping process was executed utilizing the Ordinary Kriging interpolation technique within the Arc-GIS 10.7.1 software platform. The area's average annual rainfall stretches over a range from 1228.66 to 1564.2 mm. The rainfall erosivity (R factor) was determined using average yearly rainfall data. The spatial and temporal variations in soil loss are closely linked to fluctuations in the R factor, emphasizing the critical role of rainfall erosivity in evaluating areas prone to severe erosion. This connection highlights the necessity of considering rainfall patterns and their erosive potential when identifying and assessing erosion hotspot areas [56].

The results indicate that the spatial distribution of the R factor value, as depicted in both Table 1 and Supplementary Fig. 2, confirms the existence of varying rainfall erosivity values throughout the entire basin. This variation in the R factor across different areas of the basin highlights the diverse impact of rainfall erosivity within the region. The range of calculated R-factor values across the study area varies significantly, spanning from 758.94.  $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$  in the southwestern segment of the watershed to 869.07  $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$  in the central region of the Woybo watershed. Moreover, a lower R-value signifies that the erosive potential of rainfall in the area is relatively low, which corresponds to a reduced intensity of rainfall events that contribute to soil erosion. This indicates that the study area experiences rainfall with a lesser capacity to erode soil, reflecting a generally lower rainfall intensity.

### Soil Erodibility (K) Factor

The Woybo watershed's K-factor values are made up of four distinct soil color types and four soil classes: Eutric Nitisols (Red), Humic Ferralsols (Yellow), Eutric Cambisols (Brown), and Orchic Andosols (Black). However, for the specific case of Ethiopia, Helden [34] and Hurni [35] proposed K-Factor values for each soil class with considerable attention to their color. As a result, K values in the Woybo watershed were allocated as 0.15 for Orchic Andosols (Black), 0.20 for Eutric Cambisols (Brown), 0.25 for Humic Ferralsols (Yellow), and 0.30 for Eutric Nitisols

(Red). Consequently, it has been realized that red soils have a high K-value, which advocates that they are more prone to erosion. Next to red soils, yellow soils have a K-value of 0.25 and are inherently prone to rainfall-induced erosion. Black soil has a low soil erodibility factor, making it less susceptible to raindrop detachment.

The majority of the eastern portion of the watershed is afflicted by red soils, which are extensively influenced by soil loss and erosion, and nearly all of this soil type is the stream's source. Brown soils dominate the western half of the watershed, making them more prone to raindrop detachment. Furthermore, the entire central area of the watershed is concealed by black soil, which is very resistant to raindrop detachment (Supplementary Table 2, Supplementary Fig. 3).

### Topographic Factor (LS)

The equations (Eq. 4) anticipated by Moore and Wilson [45] were utilized to compute the topographic factors (LS) in the watershed. This equation is commonly utilized to assess soil erosion caused by runoff in a particular area. The gradient and slope length are the two most important relief characteristics that influence the degree or magnitude of water erosion within the watershed area. When calculating the topographic factor, the collective impact of the slope's grade and length was taken into account. Moreover, the watershed's computed LS factor stretches over a range from 0 to 154.093 (Supplementary Fig. 4). As slopes become steeper in elevation, there is a corresponding elevation in the erosive potential of soil due to runoff, which escalates in cycle with the rapidity or velocity of the runoff water. Additionally, increased shear stress on the soil surface came from the acceleration of runoff on steeper slopes. The LS, on the other hand, comes up with inconsequentially to almost all parts of the watershed.

### Cover and Management Factor (C)

The most common land-use type in the study area is agricultural land. Shrub land and grassland use comprise a relatively small proportion of the watershed's land use categories. Based on several studies, the allocated C factor values for each land use/cover class were 0.014 for shrubland, 0.05 for grassland, and 0.15 for agricultural land (Supplementary Fig. 5, Supplementary Table 3). The region exhibiting the lowest c factor primarily lies in the northeastern direction of the watershed, characterized primarily by shrubland vegetation cover. Likewise, within the southern extents of the study watershed, there have been observations of relatively moderate c-factor, which are covered by grassland. Therefore, it is concluded that crop

and management factor contributions to soil erosion models are greater in agricultural land, followed by grassland.

### **Erosion Management (Support) Practice (P) Factor**

This study employed the Wischmeier and Smith [64] P-value computation procedure, which is detailed in depth in the methodology section. As described in the methodology section, the Woybo watershed's land use/coverage has been categorized as cultivated land, shrub land, and other land. In this study, cultivated land was classified as a six-slope class and provided *P*-values for each slope class; regardless of slope class, grasslands were grouped into other land and allotted a *P*-value of 1.00, and shrublands were allotted a *P*-value of 0.8 (Supplementary Table 4). Based on the above allocations, the study's *P* factor stretches over a range from zero (lower) to one (higher). Supplementary Fig. 6 demonstrates that the lower *p* values are distributed relatively evenly throughout the watershed, which is covered by agricultural land. On the contrary, the highest *p* values were found in the extreme east and south of the watershed, which is covered in grassland and shrubland. The moderate *p* values were obtained in the southeast and southwest directions, which have the highest slope values in the watershed [28].

### **Assessment of Soil Loss Rates**

The calculation of the annual soil loss rate was conducted through the utilization of Eq. (1), which is discussed in detail in the methodology section. It is performed by multiplying a cell-by-cell examination of the corresponding RUSLE factor values of the study area, which are R-factor, K-factor, LS-factor, C-factor, and P-factor, in ArcGIS 10.7.1, and the resulting map is depicted in Supplementary Fig. 7. In the watershed, the yearly soil loss stretches over a range from zero in the watershed's flat surfaces to more than 65 metric tons per hectare per year in the areas characterized by steeper slopes and adjacent to the riverbanks. The calculated yearly soil loss rate was split into five severity classifications based on [31, 45] to make it easier to show the output data (Table 2). These classifications are Very Severe (> 50 tons per hectare per year), Severe (30 to 50 tons per hectare per year), Moderate (15 to 30 tons per hectare per year), Slight (5 to 15 tons per hectare per year), and Very Slight (0 to 5 tons per hectare per year) classes.

Based on the computed RUSLE factor values of the study area, the estimation of yearly soil loss occurring from the given watershed area of 600.18 square kilometers was 572,611.15 tons, with a mean annual soil loss rate of 19.58 tons per hectare per year. In the watershed, with respect to

the coverage of erosion risk area, 5.87%, 2.92%, 6.13%, 14.05%, and 71.04% were classified as very severe risk, severe risk, moderate risk, low risk, and very low risk, respectively (Table 2). This evidence demonstrates that a substantial majority, exceeding 48% of the study area, is characterized by conditions indicating a low susceptibility to soil erosion.

### **Prioritization for Soil Conservation Planning**

The figure above (Supplementary Fig. 7) indicates the probable regions of soil loss in the study watershed, from which the prioritizing range is determined based on the degree of erosion affecting the soil. Those probable regions have erosion severity levels ranging from moderate to severe to very severe, requiring conservation priority of the third, second, and first-order (Fig. 2). Upon examining the outcome, it was determined that the factors of slope length (*L*) and steepness (*S*) appeared as the predominant elements within the Revised Universal Soil Loss Equation (RUSLE) framework, amplifying the phenomenon of soil erosion and contributing significantly to the observed rate of soil loss.

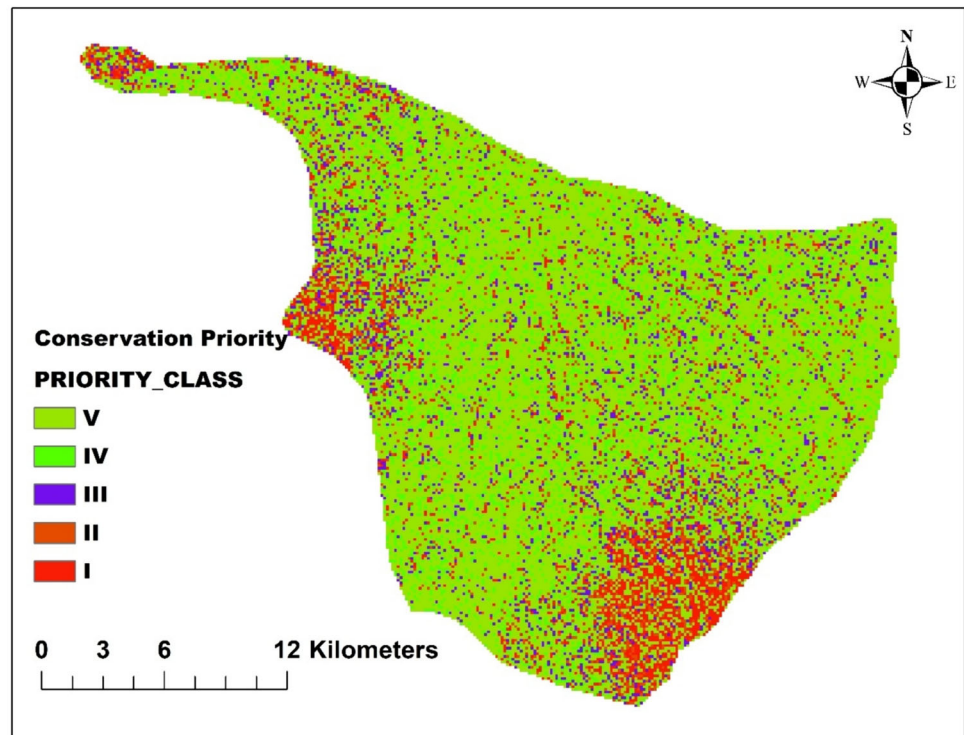
### **Conclusions**

This study customizes the empirical soil erosion model RUSLE in combination with RS and GIS to determine soil loss rates in the Woyo watershed. The RS, GIS, and RUSLE observational show created a quantitative evaluation of soil loss, which was utilized to classify the watershed region into five soil erosion hazard categories. Five RUSLE factors such as rainfall erosivity (*R*), soil erodibility (*K*), topographic (*LS*), crop and cover management (*C*), and conservation practice (*P*) factors were computed, mapped, and overlaid together to estimate the potential soil loss of the watershed. The degradation components influencing soil loss, such as high precipitation levels and Eutric Nitisols soil dominance. The amount of soil loss and degree of erosion hazard was high to severe on sloping/strongly sloping cultivated lands and poorly vegetated steep gradients. Approximately 47.78% of the watershed area experienced soil loss ranging from very slight to moderate severity, while the remaining area faced severe to very severe soil loss. The results showed that the annual soil loss rate within the watershed varied, with 18.62% of the area experiencing soil loss of 0 to 5 t ha<sup>-1</sup> year<sup>-1</sup>, 14.72% experiencing 5 to 15 t ha<sup>-1</sup> year<sup>-1</sup>, 14.44% experiencing 15 to 30 t ha<sup>-1</sup> year<sup>-1</sup>, 12.26% experiencing 30 to 50 t ha<sup>-1</sup> year<sup>-1</sup>, and 39.96% experiencing more than 50 t ha<sup>-1</sup> year<sup>-1</sup>. Overall, the watershed's annual soil erosion amounted to approximately 572,611.15 tons. The *P*



**Table 2** Soil erosion severity classes/risk levels and their respective areal coverage (in % and ha), annual soil loss (in t yr<sup>-1</sup> and %) and conservation priority

Soil loss t ha <sup>-1</sup> yr <sup>-1</sup>	Avg. soil loss t ha <sup>-1</sup> yr <sup>-1</sup>	Severity class	Area (ha)	Area (%)	Total annual soil loss (t yr <sup>-1</sup> )	Soil loss (%)	Conservation priority
0–5	2.5	Very Slight	42,637.24	71.04	106,593.10	18.62	V
5–15	10.0	Slight	8429.73	14.05	84,297.30	14.72	IV
15–30	22.5	Moderate	3676.14	6.13	82,713.15	14.44	III
30–50	40.0	Sever	1754.41	2.92	70,176.40	12.26	II
> 50	65.0	Very Sever	3520.48	5.87	228,831.16	39.96	I
Total			60,018.00	100.00	572,611.15	100.00	

**Fig. 2** Soil conservation priority classes map of Woybo watershed

values, which reflect conservation practices, ranged from 0.1 to 1. Specifically, P values of 0.1 to 0.33 were associated with agricultural land, while values of 0.8 to 1 were associated with shrubland and other land types. Soil erosion in the watershed was influenced by factors such as slope, cover and management practices, and soil erodibility (K) factor, which were used for soil classification. To ensure the long-term preservation of soil resources and prevent erosion, particularly on steeper slopes, it is essential to protect and maintain existing vegetation cover and/or replant forested areas on cultivated lands. This approach is crucial for the sustainability of soil and other natural resources within the watershed area.

Further studies should be conducted to identify the primary factors driving soil erosion losses within the farming

system. These factors include socio-economic conditions, agronomic practices, and biophysical elements that contribute to soil erosion. Understanding these drivers is crucial to developing the most effective soil and water conservation measures. By investigating the socio-economic influences, such as land use practices and economic pressures on farmers, agronomic factors, like crop rotation and tillage methods, and biophysical aspects, including soil type and topography, researchers can recommend tailored conservation strategies. These strategies should be implemented both in the specific areas affected by soil erosion and throughout the entire watershed to ensure comprehensive protection and sustainability of soil and water resources.

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## Declarations

**Conflicts of interest** The author declares that there is no conflict of interest.

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